FEASIBILITY STUDY OF NATURAL CIRCULATION BOILING WATER REACTOR BY EXAMINING THE CRITICAL HEAT FLUX REQUIREMENT

by

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CERTIFICATE

This is to certify that the present work entitled, " FEASIBILITY STUDY OF NATURAL CIRCULATION BOILING WATER REACTOR BY EXAMINING THE CRITICAL HEAT FLUX REQUIREMENT" has been carried out by Mr. Ranjan Sinha under my supervision and has not been submitted elsewhere for a degree.

March, 1994

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ABSTRACT

Recently there has been considerable interest shown in Nuclear Reactors of newer designs with simplified features.These have sought to improve the safety aspect and also to reduc the plant construction costs by simplifying features of the conventional reactors.The Natural Circulation Boiling Water Reactor is one such design which looks very promising from the point of view of future power requirements.This thesis analyses the feasibility of such reactors satisfying one of the criteria of thermal hydraulic requirement, namely the Critical Heat Flux Ratio (CHFR). The necessary riser height to ensure the minimum recirculation flow required for the CHFR stipulation has been computed using one dimensional codes.It is concluded that Natural Circulation BWRs of higher powers meets the CHFR criterion and its safe operation is definitely possible.

ACKNOWLEDGEMENT

I take this opportunity to express my sincere gratitude and thanks to Dr K.SriRam under whose guidance this work has been possible He has been a constant source of encouragement to me ,and his sincere and intelligent suggestions at crucial times has gone a long way in helping me complete this work.

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Ranjan Sinha

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CHAPTER 1

INTRODUCTION

The 1990s' has witnessed the spawning of new nuclear reactor designs in US and Japan which span the technological range from evolutionary light water and heavy water, through light water passive and gas cooled, to liquid metal fast breeder.

The likelihood of successful development and operation of any individual reactor design depends on a mix of both ' hard ' and 'soft ' variables. The hard variables are the more objective factors such as actual design characteristics, cost, length of technology leap, and degree of research and development support by the government and industrial organisations.

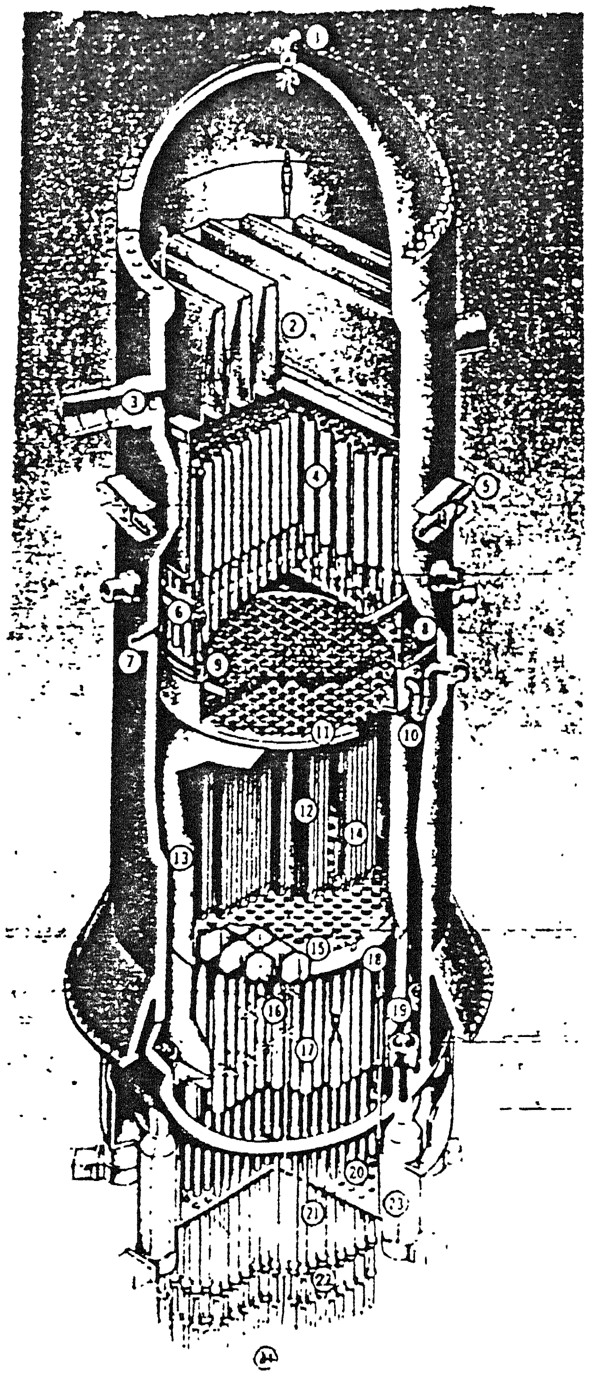
The soft variables are more ambiguous and depend more on so called ' public perception ' rather than on facts. They may involve imponderables like attitude towards carbon dioxide production and global warming, and alternative power technologies. Other factors are more nation specific, including degree of political opposition to siting of nuclear plants or radiation waste storage sites, public ambivalence towards the unknowns of the new technology versus the familiar one and the regulatory procedures. Yet other soft variables are utility specific such as size of available markets and suitability of a design's power output.

Most of the designs developed so far have aimed at increased safety and economical operation by simplifying construction, operation and maintenance because these designs have included these factors as principal objectives.

The Advanced Boiling Water Reactor (ABWR) and its smaller counterpart the Simplified Boiling Water Reactor (SBWR) are among the newer designs in BWR proposed by General Electric (GE) (Reference New Reactor[6]). The ABWR and SBWR designs are expected to show improvement over the current fleet of BWRs in plant availability, operating capacity factor, safety and reliability while reducing power generation costs, construction times, occupational radiation exposure and radioactive waste. By simplifying design of the components system and structure and by using natural circulation of coolant further improvements in safety, performance and economy can be made.

The designs of ABWR (fig 1.1) and SBWR (fig 1.2) have much in common, the only difference between them are the power rating, core flow recirculation (10 internal pumps for ABWR and natural circulation) and extent to which some of safety systems uses active versus passive features. An important characteristic of both ABWR and SBWR is the elimination of external circulation piping and therefore permits a compact containment design. It also allows elimination of large vessel nozzles below the core, and therefore the design of a more economic emergency core cooling systems. Elimination of external circulation piping results in a greater then 50 % reduction in welds, less in service inspection (ISI) of the primary system boundary, less occupational dose during ISI, increased system integrity and sizable saving in capital cost.

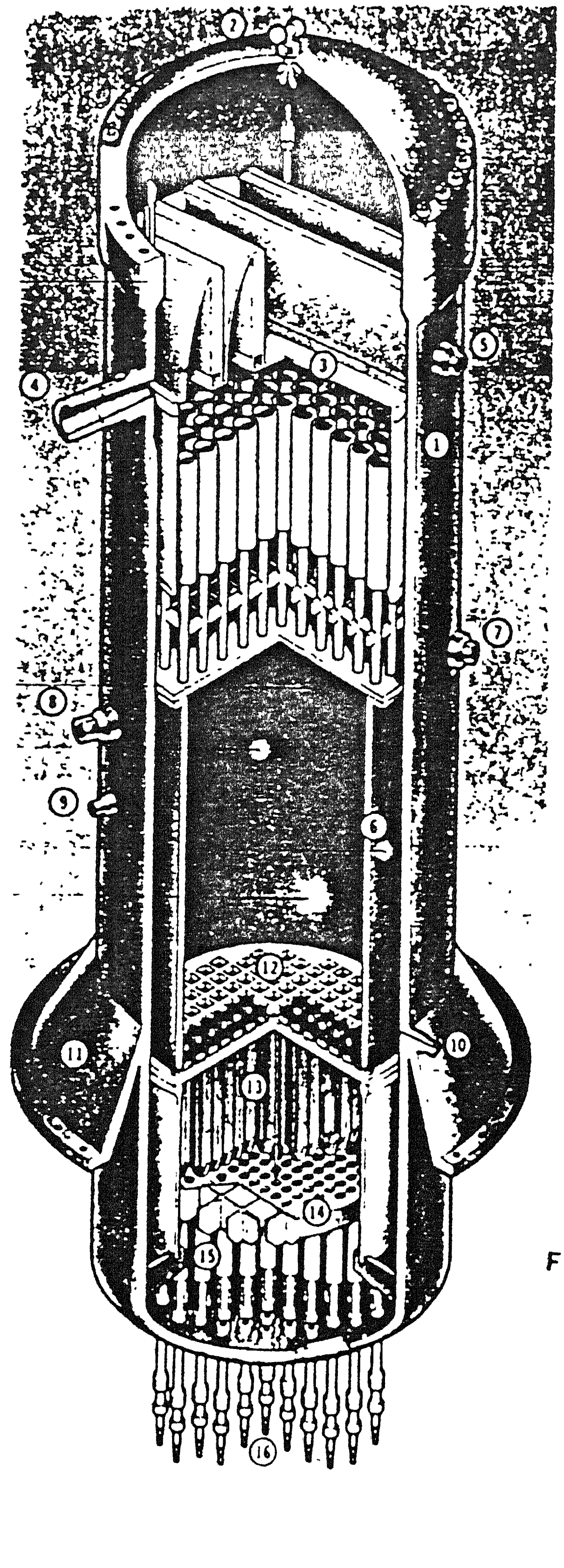
In response to the increasing interest in potential future nuclear units comprising the characteristics of smaller size, greater simplicity and more passive safety features, GE started



Advanced Boiling Water Reactor Assembly

1 Vent and Head Spray
2 Steam Dryer
3 Steam Outlet Flow Restrictor
4 Steam Separators
5 RPV Stabilizer
6 Feedwater Sparger
7 Shutdown Cooling Outlet
8 Low Pressure Flooder (LPFL) and Shutdown Cooling Sparger
9 High Pressure Core Flooder (HPCF) Sparger
10 HPCF Coupling
11 Top Guide
12 Fuel Assemblies
13 Core Shroud
14 Control Rod
15 Core Plate
16 In-Core Instrument Guide Tubes
17 Control Rod Guide Tubes
18 Core Differential Pressure Line
19 Reactor Internal Pumps (RIP)
20 Thermal Insulation
21 Control Rod Drive Housings
22 Fine Motion Control Rod Drives
23 RIP Motor Casing
24 Local Power Range Monitor

Fig. (1.1) Advanced Boiling Water Reactor Assembly.



Simplified Boiling Water Reactor Assembly

1 Reactor Pressure Vessel
2 RPV Top Head
3 Integral Dryer-Separator Assembly
4 Main Steam Line Nozzle
5 Depressurization Valve Nozzle
6 Chimney
7 Feedwater Inlet Nozzle
8 Reactor Water Cleanup/Shutdown Cooling Suction Nozzle
9 Isolation Condenser Return Nozzle
10 Gravity-Driven Cooling System Inlet Nozzle
11 RPV Support Skirt
12 Core Top Guide Plate
13 Fuel Assemblies
14 Core Plate
15 Control Rod Guide Tubes
16 Fine Motion Control Rod Drives

Fig.(1.2) Simplified Boiling Water Reactor Assembly.

studies in 1987 of a 600 MWe BWR with simplified power generation, safety and heat removal systems. The basic objectives that were established for this new design SBWR are

- Power generation cost to be cheaper than those of coal.
- Plant safety design simpler than in current design by using
- passive safety concepts.
- Design based on existing technology.
- Shorter construction schedules.
- Electrical rating in the 600 MWe range.
- Improve the seismic resistance of the core.
- Lengthen the continuous operating period.
- Simplify the system by eliminating movable components.
- Improve the operability and the maintainability.

Selection of the natural circulation as the means for providing coolant flow through the reactor, coupled with a 42 Kw/l core power density, results in a number of benefits to help satisfying SBWR objectives, Compared to the existing, forced circulation plants, the natural circulation BWR offers low fuel cycle costs, fewer operational transients, and increased thermal margin for the transients expected to occur. In addition, elimination of the recirculation, pumps and controls needed for forced circulation substantially simplified the design. (fig 1.3)

Conventional BWR safety / relief valves - which opens and closes to discharge reactor vessel steam to suppression pool - are not needed in SBWR because in it an isolation condenser is placed in the isolation condenser pool so when the reactor vessel is isolated from the turbine condenser, the isolation condenser controls the reactor pressure automatically without the need to

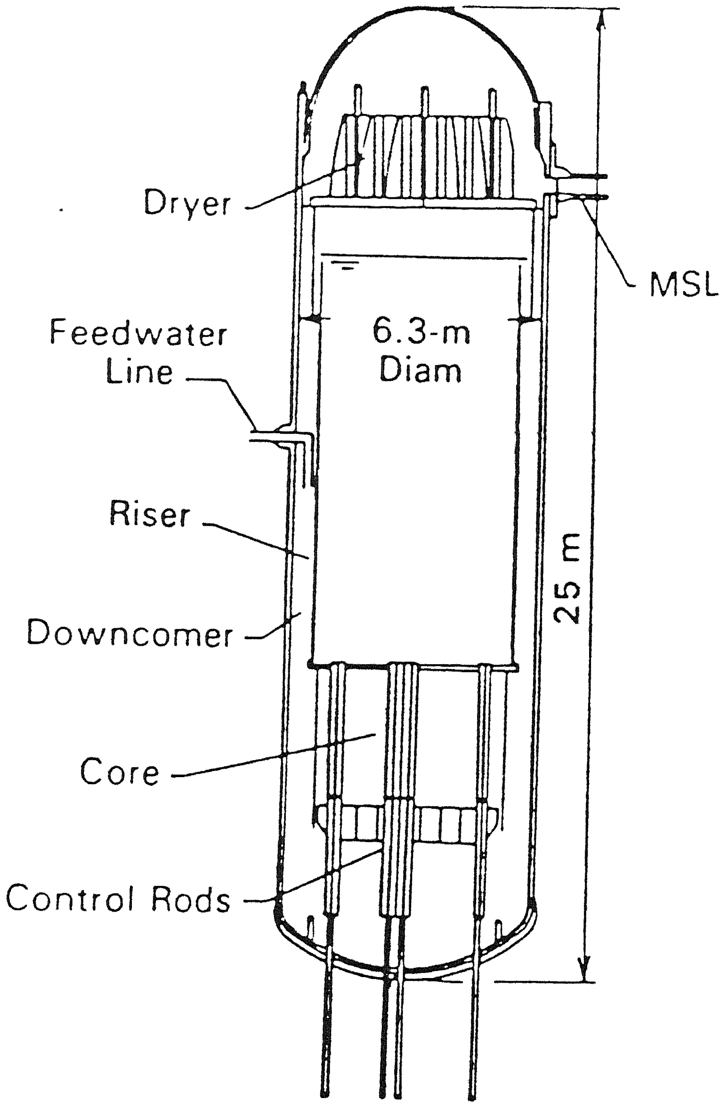


Fig.(1.3) Schematic of Reactor Pressure Vessel of SBWR.

remove fluid from the reactor vessel.

Gravity-driven core cooling system provide a simple approach to emergency core cooling system because it eliminates the need of pumps. Simplification of the components and the system made the primary containment vessel and reactor building smaller which reduces the radiation exposure and construction cost substantially.

CHAPTER 2

PRINCIPLE OF NUCLEAR REACTORS

2.1 Introduction:

The thermal energy produced in a fission power plant is the kinetic energy of the fission fragments and to a lesser extent of the emitted neutron and other particles and radiation such as gamma rays which get converted to heat when these particles are absorbed. This heat is removed by a coolant and subsequently utilized in a thermodynamic cycle.

Nuclear reactors are variously classified according to general purpose or function, type of the moderator, type of the coolant, neutron energy classification, type of fuel, type of core internal design and other factors.

While the other possible coolant besides light water can be used like the heavy water, organic liquid, gases and liquid metals, light water has been used most extensively , because of its availability, low pumping power and the advanced state of knowledge concerning its chemistry and thermodynamics properties etc.

2.2 Light Water Reactors:

The reactor in which the coolant is light water may be broadly divided into PWR and BWR. As the names suggest, Boiling Water Reactors are those in which the water boils within the reactor, and in Pressurised Water Reactor the pressure is high to avoid boiling. Thus the water pressure corresponds to the saturation temperature at the reactor pressure in a BWR. The reactor pressure is roughly between 600 and 1000 psia. A schematic

arrangement of a BWR is shown in the figure(2.1)

In a Pressurised Water Reactor, reactor pressures are higher and of the order of 2000 psia, for the primary coolant loop within the reactor. A heat exchanger in which the primary coolant exchanges heat with a secondary coolant is used. A schematic sketch of a PWR is shown in the figure(2.2)

However, in this study, we focus our attention on the former type of reactor that is the BWR. The boiling reactor has a function closely resembling that of boiler in a conventional fossil-fuel steam power plant and is basically simpler than it. While in a boiler heat is transmitted from the furnace to the water indirectly - partly by radiation, partly by convection and partly by conduction; with combustion gases acting as an intermediate agent or coolant, in the Boiling Water Reactor, the coolant is in direct contact with the heat producing nuclear fuel and boils in the same compartment in which the fuel is located.

The simplest form of a boiling reactor power plant as shown in the figure(2.3)consists of a reactor, a turbine generator, a condenser and the associated equipments (such as ejector, cooling system etc.) and a feed pump to force the incoming coolant to core. Slightly sub-cooled liquid enters the reactor core in the bottom where it received the sensible heat for saturation plus latent heat for vaporisation. When it reaches the top of the core it has been converted to a very wet mixture of liquid and vapor. The vapor separates from the liquid, flows to the turbine, does work and is condensed by the condenser, and the condensate is then pumped back to the reactor by the feed pump. That is how the power is generated in the conventional BWR. Such a cycle is called

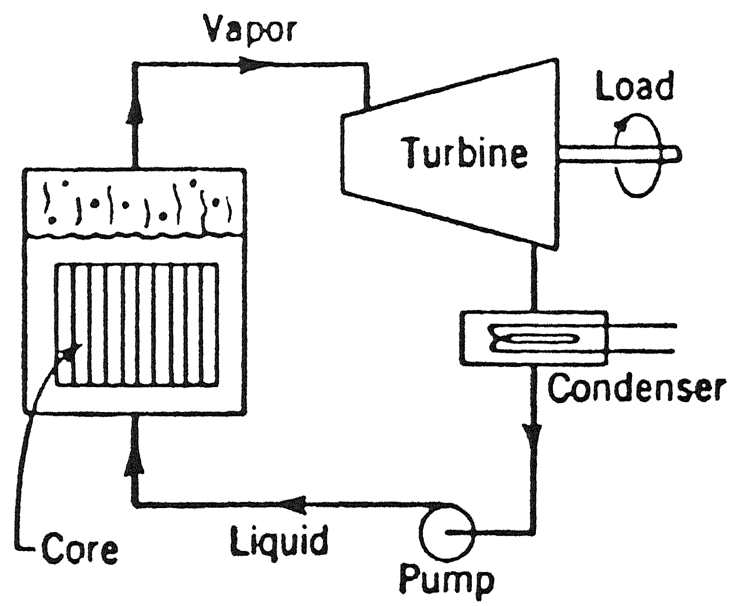


Fig 2.1 Schematic arrangement of boiling-reactor power plant.

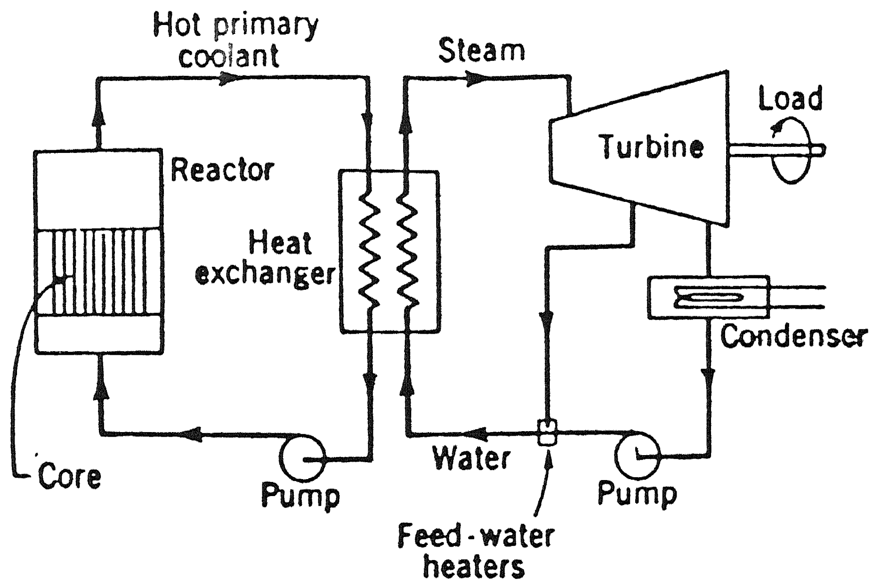


Fig 2.2 Schematic arrangement of liquid-cooled-reactor power plant.

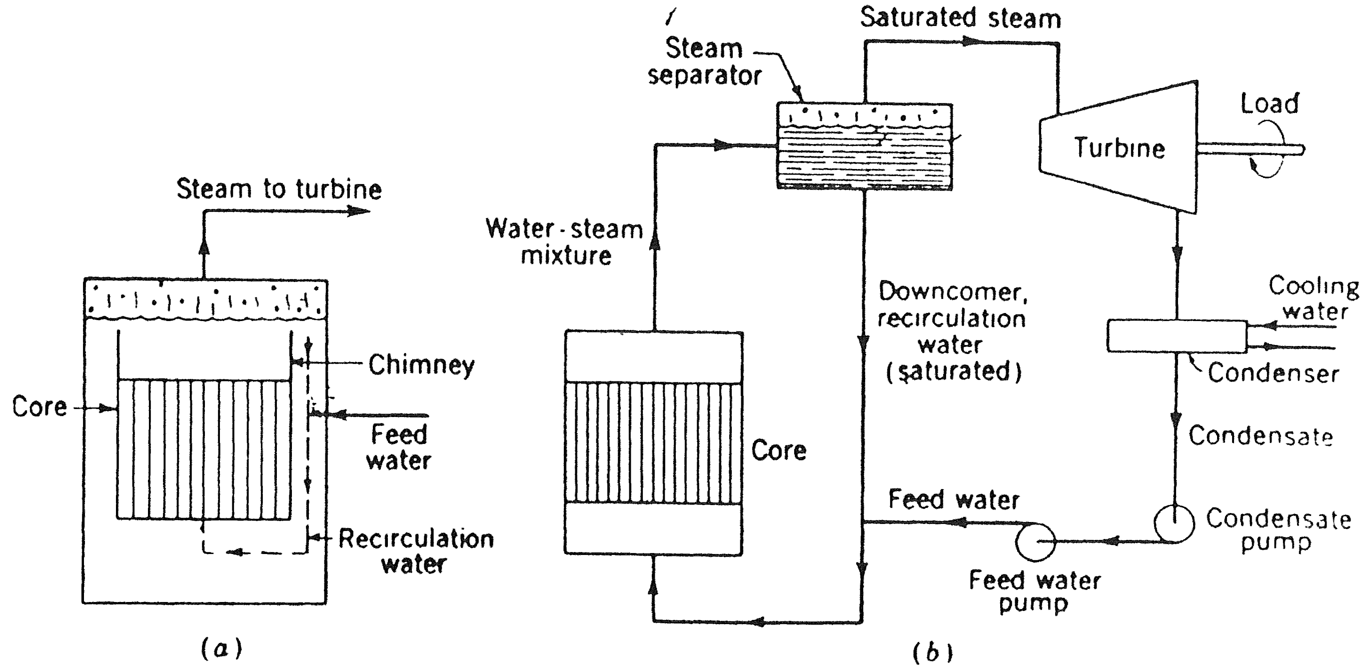


Fig. 2.3 Simple boiling-water-reactor systems. (*a*) Internal recirculation; (*b*) external recirculation.

direct cycle BWR, which has the disadvantage of primary coolant coming in contact with turbine etc. To overcome this problem one can employ indirect cycle BWR in which a heat exchanger is used to separate the radioactive primary coolant from the non-radioactive secondary coolant.

2.3 Natural Circulation BWR:

The simplified and modified version of the conventional BWR is the natural circulation BWR, more generally known as Simplified Boiling Water Reactor (SBWR). The present thesis deals with this simplified BWR. Except for the neutronic / thermal-hydraulic design, there is no difference between the design of natural circulation BWR and forced circulation BWR. In the natural circulation BWR the necessary recirculation flow ~~fore~~ core cooling will be produced by the driving force originating from the buoyancy due to density head difference in the closed loop of the recirculation flow. (in the absence of recirculation pumps)

Actually the technology for the natural circulation is not new to BWR. The Dodewaard plant in Netherlands has operated on this principle at a life time capacity factor of 84%. Larger BWRs have been operated at 50% power levels in natural circulation mode to prove that BWR of this type is indeed possible.

A schematic of the natural circulation BWR as it contrasts with the forced circulation BWR is shown in the figure(2.4). The major design aspects of the natural circulation BWR has been shown in the figure (2.5).

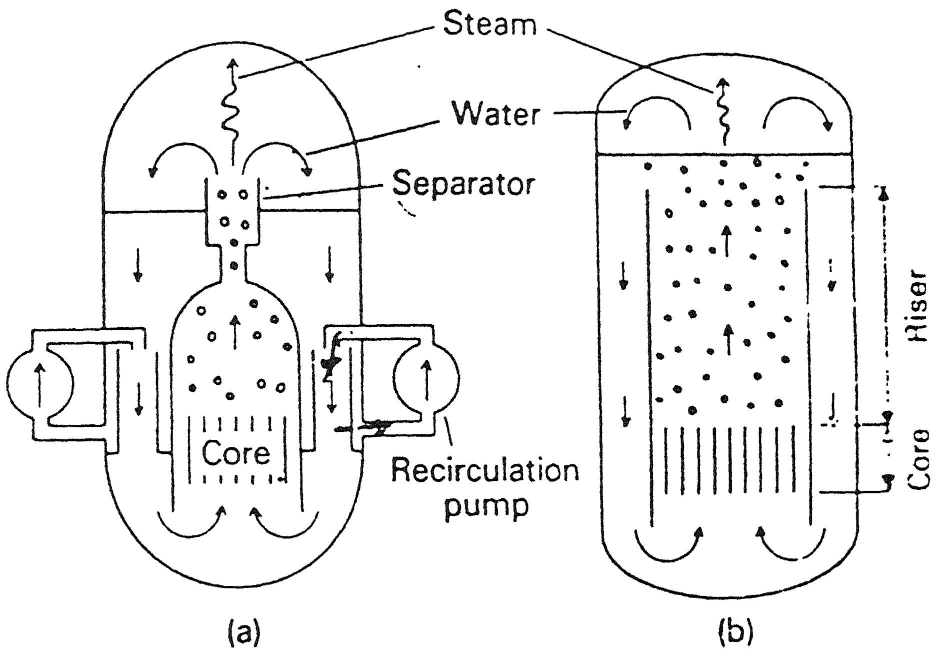


Fig.2.4 Schematic of (a) forced-circulation BWR and (b) natural-circulation BWR.

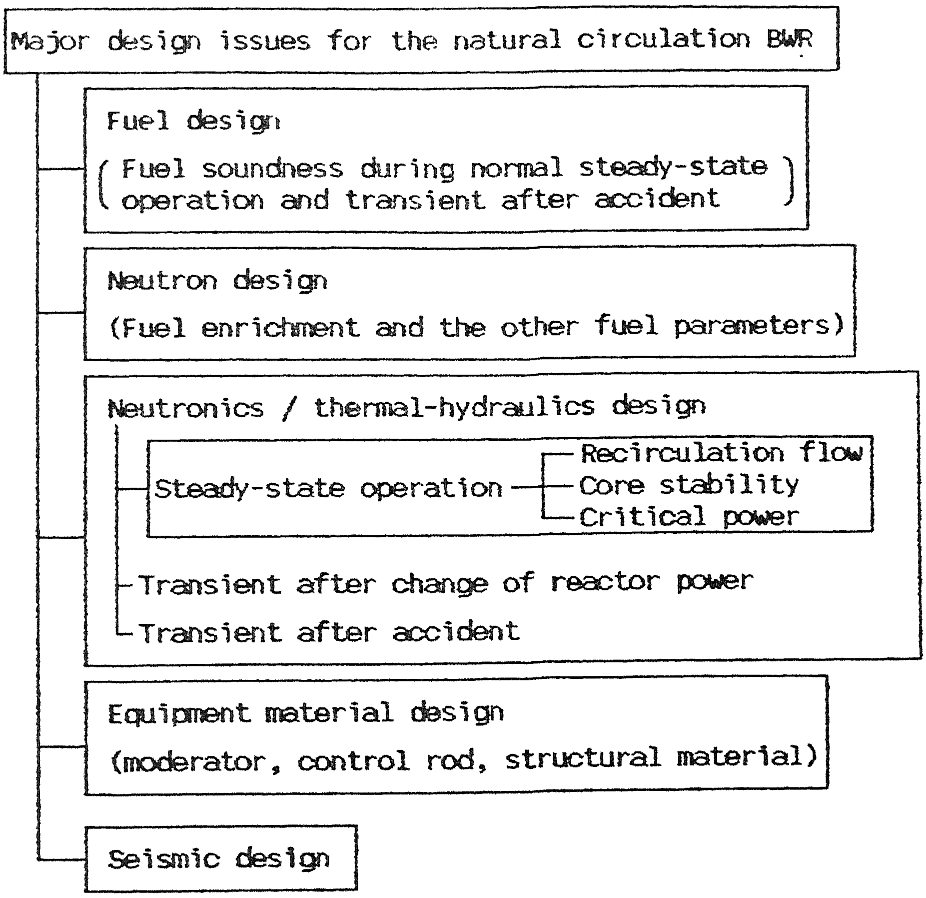


Figure (2.5): Major design aspects of natural circulation BWR

CHAPTER 3
PROBLEM STATEMENT AND PROCEDURE

For determining the feasible power rates for the natural circulation BWR , the design criteria for steady thermal hydraulics ie the critical power and core stability should be satisfied. The feasible power rates from the point of view of critical power requirements has to be determined.

FLOW MODEL: The flow in the riser ,downcomer and parallel core channels was assumed to be vertically one dimensional. A code was developed to find out the minimum core flow necessary to meet the critical heat flux requirements. The input parameters of the code are the total power, inlet flow sub cooling and the core operating pressure.

Next a code was developed which computes the total pressure drops in the respective parts of the recirculation flow formed by the downcomer -core & riser and the necessary riser height to ensure the driving pressure for natural circulation.

The critical heat flux ratio has been taken to be greater than 1.3 from safety considerations. It is assumed that the selected requirements for CHFR are conservative enough to give an over all inherently safe reactor.

the procedure has been outlined in the following fig

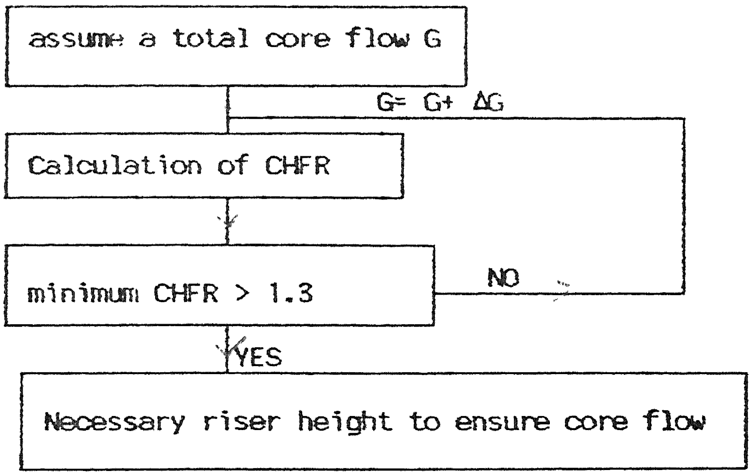


figure 3.1:outline of procedure for calculation of riser height

CHAPTER 4

CRITICAL HEAT FLUX REQUIREMENT

4.1 Introduction

The liquid coolant used in nuclear reactors is subjected to high rates of heat fluxes .In boiling water reactors , the change of phase is deliberately designed into the system and should be controlled. The conditions at which the heat transfer coefficient of the two phase flow substantially deteriorates is called the critical heat flux condition (CHF) For a given flow conditions, it occurs at sufficiently high heat flux or wall temperature.In a system, in which the heat flux is independently controlled , the consequences of CHF occurrence is the rapid rise in the wall temperature .For systems in which the wall temperature is controlled , the occurrence of CHF implies a rapid increase in the heat flux.

Many terms have been used to denote the CHF conditions, including "boiling crisis" and " burnout".Departure from nucleate boiling (DNB) is the term originally used to describe the CHF conditions in pool boiling. It can also be encountered in flow boiling , when the formation is rapid enough to cause continuous vapour film at the wall. Generally the CHF has been calculated using both the criteria of (a) Departure from nucleate boiling and also from (b)dryout.

4.2 Critical Power Ratio(CPR)

To eliminate the undesirable features inherent in the local CHF hypothesis a new correlation known as the General Electric critical quality- boiling length (GEXL) correlation was developed.The GEXL correlation is based on a large amount of

boiling transition data taken in General Electric's ATLAS Heat Transfer Facility .The Generic form of the GEXL correlation is

$x_{cr} = x_{cr}(\ l_b,\ d_h, g, l, p, R)$.....(4.1)

where x_{cr} = bundle averaged critical quality

l_b = boiling length

d_h = equivalent diameter of channel

l = total heated length

p = system pressure

R= parameter that characterises the local peaking pattern

The GEXL correlation is a "best fit " to the experimental data and said to be able to predict a large range of data.The GEXL correlation is a relation between parameters that depend on the total heat input from the channel inlet to a position within the channel. This correlation line is plotted in terms of critical bundle radially average quality vs the boiling length. For a given bundle power ($\dot{Q}_1$,or $\dot{Q}_2$) the locus of bundle conditions can be represented in the fig 4.1 The critical power of a bundle is the value of bundle power to which the correlation line becomes becomes a tangent.The critical quality - boiling length leads to a identification of a new margin of safety in BWR designs ie the Critical Power Ratio. CPR = $\frac{\text{critical power}}{\text{operating power}}$.

4.3 Critical Heat Flux Ratio Correlation

In absence of the GEXL correlation ,(it being a proprietary information) we take recourse to the CHF Correlations as given by Biasi.(Todreas & Kazimi [7])

$$q''_{biasi}=(2.764\cdot10^{7})(100D)^{-n}G^{-1/6}\left[1.468F(p_{bar})G^{-1/6} - x\right]W/m^{2} \quad ....(4.2)$$

$$q''_{biasi}=(15.048\cdot10^{7})(100D)^{-n}G^{-1/6}H(p_{bar})[1- \ x]\ \ W/m^{2} ....(4.3)$$

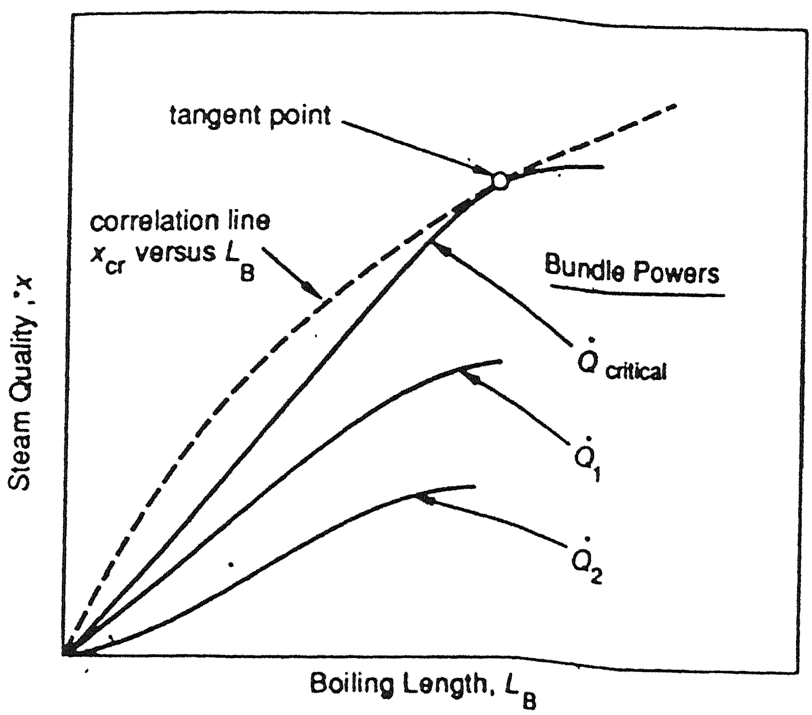


Figure 4.1 Correlation of critical conditions under dryout.

The greater of the above two values is taken where

$$F(p_{bar}) = 0.7249 + 0.099\cdot(p_{bar})\cdot\exp(-\ 0.032\ p_{bar}) \quad \ldots(4.4)$$

$$H(p_{bar}) = -1.159 + 0.149\ p_{bar}(\exp(-0.019\ p_{bar}) + 9\ p_{bar}(10 + p_{bar}^{2})^{-1} \quad \ldots(4.5)$$

p_{bar} = 10p where p is in Mpa

the equivalent diameter D = 4·area/ wetted perimeter.

$$n = \begin{cases} 0.4 \text{ when } D \geq 0.01 \\ 0.6 \text{ when } D < 0.01 \end{cases}$$

The quality x(z) has been computed as

$$x(z) = \frac{q_{cr}}{\dot{m} h_{fg}} - \frac{\Delta h_{sub}}{h_{fg}} \quad \ldots(4.6)$$

where x(z) = quality at any height z

$\dot{m}$ = mass flow rate

Δh_{sub} = degree of sub cooling

The pattern of heating has been taken to be uniform and the axial peaking factor to account for the sinusoidal heat addition has been taken to be 1.57.An iterative scheme was developed as under.

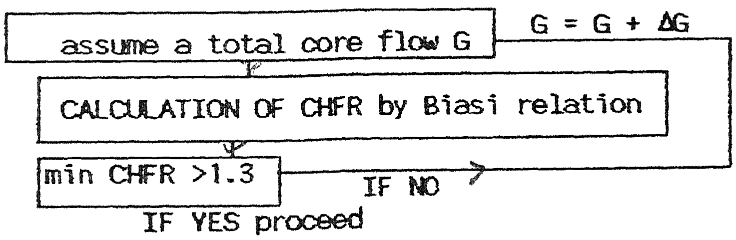


fig 4.2:outline for calculation of min G

For the two power densities of 42 and 50 kw/lit the CHFR is plotted against G . Also the minimum G required for CHFR to be greater than 1.3 for different fuel lengths is shown in the Table 7.2

CHAPTER 5

RISER HEIGHT CALCULATION

While the last chapter looked at the necessary minimum core flow to ensure that the reactor was safe from the critical heat flux considerations, the present chapter evaluates the necessary riser height to ensure the required core flow by natural circulation .The equations developed in this chapter are from El-Wakil. [5]. To compute the necessary height the approach has been to equate the two :

(1)pressure drop components as the coolant flows through the various components and

(2) the " gravity head " that is available because of the density differential between the liquid in the core& riser and the liquid in the downcomer.

5.1. ratio of non - boiling to boiling height

In order to correctly evaluate the pressure drops as well as the average density in a boiling channel (necessary for evaluating the driving head in a natural circulation reactor) it is required to calculate the boiling and the non - boiling heights in the channel.The non - boiling height H_0 is that in which only the sensible heat is added to the incoming sub cooled coolant at the channel bottom.The remainder of the channel is that in which the boiling takes place.(H_B).

The ratio H_0/H (H: total length of channel) may be evaluated from the ratio of sensible added to the total heat added.as given below.

$$\frac{q_s}{q_t} = \frac{h_f - h_i}{(h_f + x_e \cdot h_{fg}) - h_i} \quad .....(5.1)$$

where q_s = sensible heat added per mass flow rate of incoming

coolant

q_t = total heat added per mass flow rate of incoming fluid.

h_i = enthalpy of incoming coolant to the core.

In case of sinusoidal heat addition (extrapolation lengths neglected) the area bounded by $z = 0$ to $z = H_0$ is proportional to the q_s and the total height to the q_t. It can be written as

$$\frac{q_s}{q_t} = \frac{\int_0^{H_0} q_\ell \sin\left(\frac{\pi z}{H}\right) dz}{\int_0^{H} q_\ell \sin\left(\frac{\pi z}{H}\right) dz} = 0.5\cdot\left(1 - \cos\left(\frac{\pi H_0}{H}\right)\right) \quad .....(5.2)$$

5.2 pressure drop components:

5.2.1 friction drop in core channel

In the boiling height H_0, friction is due to single phase(liquid only) flow and may be evaluated by Darcy's formula.

$$\Delta p_{sp} = f \frac{H_0}{D_e} \frac{\rho v^2}{2} \quad .....(5.3)$$

where Δp_{sp} = single phase pressure drop

f = friction factor dependent upon Reynold's no.

D_e = equivalent dia of channel given by

4· channel area/(wetted perimeter)

ρ = average density in non - boiling height

v = average velocity in the non - boiling height

pressure drop in boiling height :

In the boiling height the pressure drop due to friction is greater than that due to single - phase liquid flow for the same flow rate.

The two phase drop as it compares with a calculated friction drop, assuming that only saturated liquid existed in the channel is given by $R = \frac{\Delta p_{tp}}{\Delta p_{sp}}$ ....(5.4)

where R = two phase friction multiplier

Δp_{tp} = two phase pressure drop in boiling height only

Δp_{sp} = saturated liquid phase pressure drop in the same height

R is found to be a function only of the exit void fraction and independent of the many operating conditions such as pressure , heat flux , coolant flow rate and slip ratio.

The Lottes' Flinn correlation has been used which is given by

$$R = \frac{1}{3} \cdot \left[1 + \frac{1}{1 - \alpha_e} + \left(\frac{1}{1 - \alpha_e} \right)^2 \right] \quad ......(5.5)$$

where α_e = exit void fraction

5.2.2 acceleration pressure drop

As the coolant receives heat in the core channel , it undergoes an increase in volume, consequently it has to accelerate as it travels through the channel .The acceleration pressure drop has to be evaluated from the relationship involving the change in momentum of the incoming and outgoing fluids.Force F due to the change in the momentum is given by

$$F = \Delta p_a A_c = \dot{m}_f v_{fe} + \dot{m}_g v_{ge} - \dot{m}_t v_i \quad ....(5.6)$$

where Δp_a = pressure drop due to acceleration or change in momentum,

A_c = crossectional channel area,

v_i= inlet velocity to channel

v_{fe}, v_{ge}, = velocities of saturated liquid and of vapour respectively

eqn 5.6. can be derived as $\Delta p_a = r \cdot G^2$ where r is

$$= v_f \cdot \left[\frac{(1 - x_e)^2}{(1 - \alpha_e)} + \frac{x_e^2 \cdot v_g}{\alpha_e \cdot v_f} - 1 \right] ......(5.7)$$

v_f = saturated specific volume

v_g = saturated vapour velocity

v_f = saturated liquid velocity

5.2.3 expansion losses in two phase flow

Because of sudden area changes as they flow in reactor channels, two phase mixtures undergo changes in pressure, for eg. when such mixture leaves the fuel channel to enter the riser.(common to all the fuel elements). Force balance across the expansion is written as : (fig 5.1)

$$p_1 A_2 + m_{f1} \cdot v_{f1} + m_{g1} \cdot v_{g1} = p_2 \cdot A_2 + m_{f2} \cdot v_{f2} + m_{g2} \cdot v_{g2}$$

the eqn reduces to

$$p_2 - p_1 = \left(\frac{1}{A_1 \cdot A_2} - \frac{1}{A_2^2} \right) \cdot \dot{m}_t^2 \left[\frac{(1 - x_e)^2}{\rho_f (1 - \alpha)} + \frac{x^2}{\rho_g \cdot \alpha} \right] \quad ....(5.8)$$

5.2.4 contraction losses in single phase flow

The area contraction results in a vena contracta of area A_o following the contraction (fig 5.2). Contraction loss is assumed solely due to the expansion of the fluid from the vena contracta to the point where the fluid fills the area A_2.The contraction loss occurs when the fluid enters the fuel channels.(from the bottom) For single phase it may be written as

$$p_2 - p_1 = 0.7 \cdot \left(\frac{1}{A_1^2} - \frac{1}{A_2^2} \right) \cdot \frac{\dot{m}_t^2}{\rho_f} \quad .....(5.9)$$

where $\dot{m}_t$ is the mass flow rate

5.3 DRIVING PRESSURE IN NATURAL CIRCULATION

The water in the downcomer is either saturated or slightly sub cooled, depending upon where the feed water is added to recirculation water.Let the density in the downcomer be given by ρ_{dc} The riser height is an unheated extension of the core but usually with fewer walls,dividers,and ofcourse , with no fuel

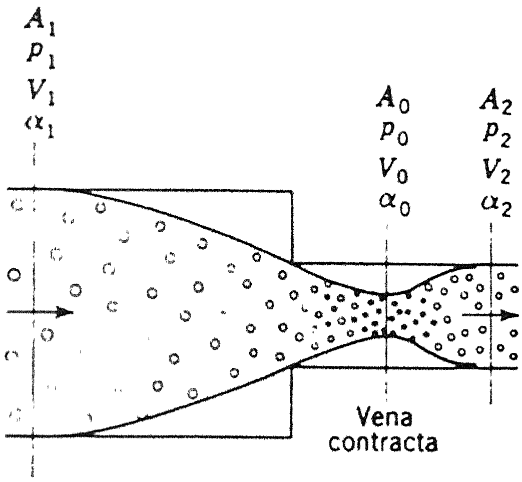


Fig. . 5.2. Single phase flow in sudden contraction

elements so that there is less friction than in the core .The quality in the riser is substantially the same as that at the channel exit, that is $x_{ch} = x_e$. The slip ratio in the riser is assumed to be same as in the core .The density along the riser is also the same as that at the core outlet. It can be readily seen that the addition of riser also increases the driving pressure by the quantity $(\rho_{dc} - \rho_e)H_{CH}$ g.The driving pressure in the case of channel with chimney is given by

$$\Delta p_d = [\ \rho_{dc}(H + H_{CH}) - (\bar{\rho}H + \rho_e^{*CH})]\ g \quad ...(5.10)$$

where $\bar{\rho}$= average density in channel given by

$(\rho_o Ho + \rho_b\ HB)/\ H$ where ρ_o is the average density in the non - boiling channel,ρ_b the average density in the boiling channel. ρ_o may be closely evaluated as the inverse of the average specific volume in the non - boiling channel as follows $\frac{1}{\rho_o} = 0.5\cdot(v_i + v_f)$.

For the case of sinusoidal heat addition in the channel an expression of ρ_b can be derived .Taking a differential element of height dz at height z within the boiling region (that is z > Ho) The density of the two phase mixture is given by

$$\rho_z = (\ 1 - \alpha_z)\ \rho_f + \alpha_z \rho_g = \rho_f - \alpha_z(\ \rho_f - \rho_g) \quad ...(5.11)$$

average density will therefore be given by

$$\rho_b = \frac{1}{HB} \int_{HO}^{H} \left[\rho_f - \alpha_z(\rho_f - \rho_g)dz\right] \quad ...(5.12)$$

To integrate this equation , a relationship between α_z (the void fraction at z) and z must be obtained .

.First a relationship between α_z and x_z,the quality at z is obtained as $\alpha_z = \dfrac{x_z}{\psi + (1 - \psi)\cdot x_z}$ ..(5.13)

This is done by by relating z to the heat addition as follows

$$q_z = (h_f + x_z \cdot h_{fg}) - h_i \quad \ldots(5.14)$$

$$q_t = (h_f + x_e h_{fg}) - h_i \quad \ldots(5.15)$$

where q_z = heat generated and transferred up to height z and q_t = total heat generated (per mass flow rate). For sinusoidal heat addition , the case under consideration; the above two quantities are related by an expression as $\frac{q_z}{q_t} = 0.5 \cdot \left(1 - \cos\frac{\pi z}{H}\right) \ldots(5.16)$

The solution to integral is obtained as follows

(a) for $c_3^2 > c_4^2$

$$\rho_b = \rho_f - (\rho_f - \rho_g) \cdot \left[\frac{c_2}{c_4} + \frac{c_1 \cdot c_4 - c_2 \cdot c_3}{c_4 \sqrt{c_3^2 - c_4^2}} \frac{H}{H_B} \cdot \right.$$

$$\left. \left\{ 1 - \frac{2}{\pi} \tan^{-1} \frac{(c_3 - c_4) \tan\left(\frac{\pi H_0}{2H}\right)}{\sqrt{c_3^2 - c_4^2}} \right\} \right] \ldots(5.17)$$

(b) for $c_4^2 > c_3^2$

$$\rho_b = \rho_f - (\rho_f - \rho_g) \left[\frac{c_2}{c_4} - \frac{c_1 \cdot c_4 - c_2 \cdot c_3}{c_4 \sqrt{c_4^2 - c_3^2}} \frac{H}{H_B} \cdot \frac{1}{\pi} \right.$$

$$\left. \ln \frac{(c_4 - c_3) \tan\left(\frac{\pi H_0}{2H}\right) + \sqrt{c_4^2 - c_3^2}}{(c_4 - c_3) \tan\left(\frac{\pi H_0}{2H}\right) - \sqrt{c_4^2 - c_3^2}} \right] \ldots(5.18)$$

$$\left.\begin{aligned} \text{where } c_1 &= \frac{q_t}{2h_{fg}} - \frac{h_f - h_g}{h_{fg}} \\ c_2 &= -\frac{q_t}{2h_{fg}} \\ c_3 &= \psi + (1-\psi)\, c_1 \\ c_4 &= (1-\psi) c_2 \end{aligned}\right] \ldots(5.19)$$

The density of the liquid in the downcomer is assumed to be the same as that of the saturated liquid because of the high recirculation ratio.

CHAPTER 6

FLUID FLOW PATTERN IN MULTI CHANNEL CORE

In chapter 5 the riser height has been computed assuming that the heat generated in the core is uniform radially.Actually, the neutron flux distribution in the radial direction is never really uniform; the amount of heat generated by the the fuel differs from one channel to another.The amount of steam generated and consequently the exit quality vary from one channel to another. In a natural circulation reactor, the driving pressure is therefore not equal in all channels, being greatest for those channels with the highest neutron flux(ie near the core center) and least near the core periphery.The coolant flows in the different channels also vary in the same order.

For calculation of the fluid flow pattern , the core is divided into a no. of regions, each containing a no. of fuel channels.These region are chosen so that each contains fuel channel at the same neutron flux level.These regions do not necessarily contain the same no. of fuel channels, nor are they necessarily adjacent to each other. for example in the fig 6.1 a 72 fuel assembly has been divided into 4 regions containing the following no. of fuel channel

region	no of fuel channel
A	16
B	20
C	24
D	12

In our case the core has been divided into 7 regions . A code was developed that computed the distance of the centroid of the fuel

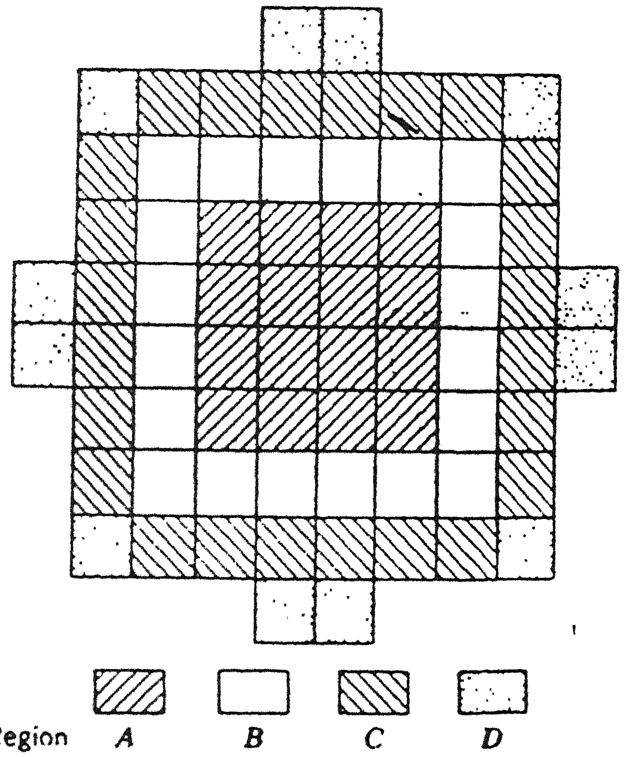


Fig. 6.1. Top view of 72-fuel subassembly core, divided into four regions.

channel from the core center. and accordingly divided the core as

	RANGE (in m)	NO OF FUEL CHANNELS
A	0 - 0.6	60
B	0.6 - 1.0	104
C	1.3 - 1.6	112
D	1.6 - 1.9	176
E	1.9 - 2.1	224
F	2.1 - 2.3	100
G	2.3 and above	96
	Total =	872

For calculation it is assumed that the data given are the ~~the~~ total core thermal power , the core operating pressure, the inlet flow sub cooling, the general core design ,and the core shape.The quantities to be computed are the riser height and the core flow pattern. The steps outlined are

(1) The heat generated in each of the regions has been calculated using the total core power and the neutron flux distribution. The heat generated is assumed to vary according to Jo (the Bessel function).

(2) the core average exit quality has been computed from the total core thermal power and assuming the total flow through the core.

(3) Starting with the region of max. heat generation , a value of the exit quality is assumed .

(4) The total flow in the hot region is calculated using the total heat generated . Using the axial flux distribution (sinusoidal) the non - boiling and the boiling heights are computed.The pressure losses in that region are computed.

(5) The pressure drops in the downcomer are computed using the

total flow.

(6) The riser height is computed using the procedure outlined in chapter 5

(7)An exit quality for other regions is assumed.The flow and corresponding pressure losses in that region is computed using the riser height in (6). From the x_e assumed and the axial flux distribution , the average density , and the driving pressure for that region is calculated.This driving pressure is compared with the losses in that region plus those of the downcomer. If the two values are not equal then it is necessary to assume another value for x_e and recalculate until equilibrium is attained.

(8) This step is repeated for each of the regions.This fixes the value of flow and the exit quality at each of the regions.

(9) With these values the total core flow and the average exit quality are calculated. This is then compared with (2)

Steps (2) to (9) are repeated till the two values are equal.This gives the core flow pattern and the riser height.This procedure has been done for two values of core average flow of 6.0 & 9.6 kg/s bundle.The flow distribution has been shown in Tables 7.5 & 7.6.

CHAPTER 7
RESULTS AND DISCUSSION

7.1.1 variation of CHFR with core flow

As the recirculation flow increases , the critical Heat flux ratio is found to increase .This is shown in fig 7.1,wherein the CHFR increases with the recirculation flow.This is done for two power densities of 42 & 50 kw/lit.Therefore the margin of safety according to CHFR improves with increase in recirculation flow.The change in minimum recirculation flow with change in active fuel length has been shown in the fig 7.2 (for the CHFR to be greater than 1.3)

7.1.2 necessary riser height

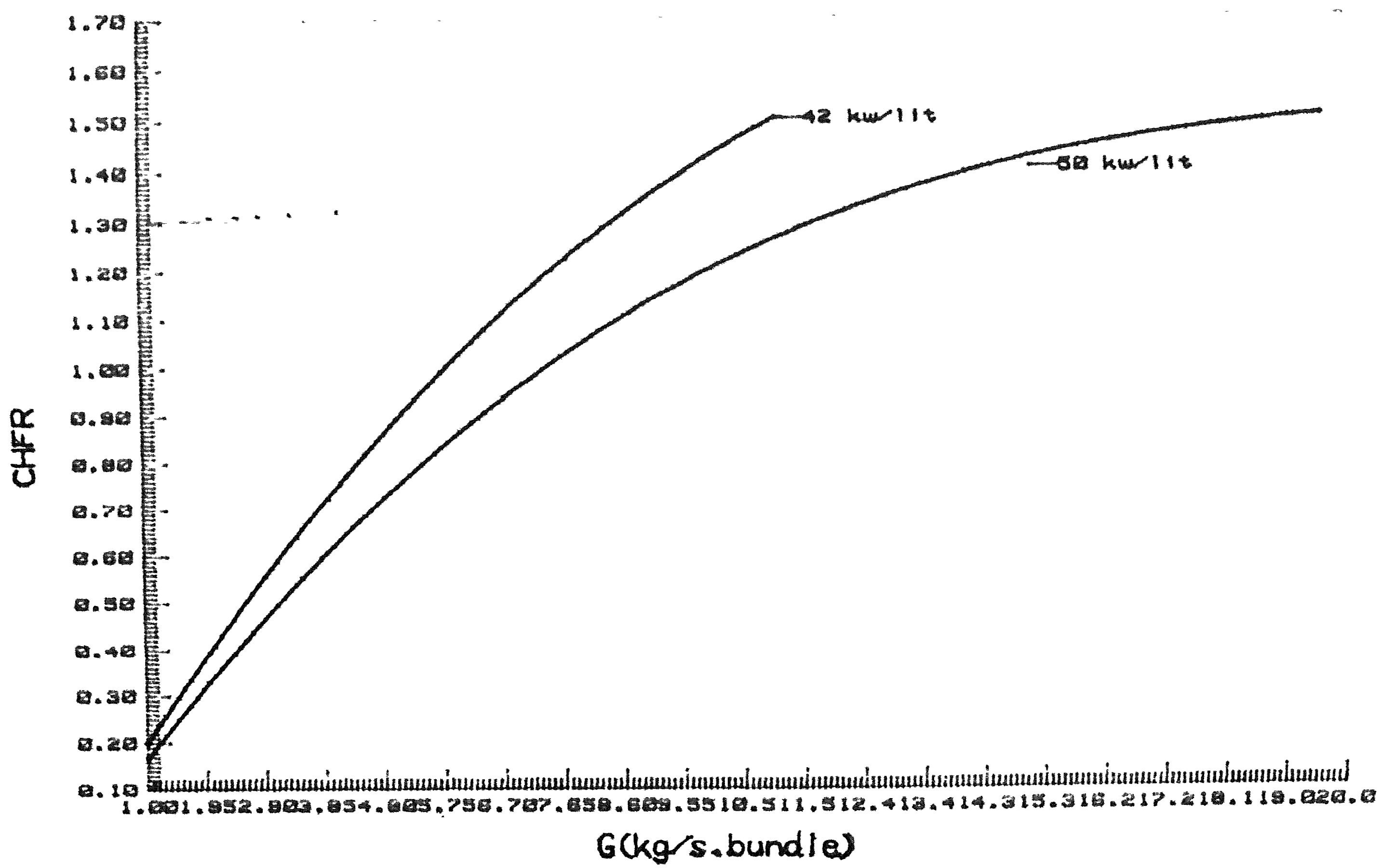
Following the procedure outlined in the chapter 5, the riser height was computed to produce the necessary minimum recirculation flow This has been done for the power densities of 42 & 50 kw/lit These are shown in the fig 7.3 .The riser height is found to increase with the active fuel length but at higher power densities it increases at a much more rapid rate. The change in riser height with power densities is shown in the fig 7.4.This is done for different active fuel lengths . According to the results of this study,the necessary riser height is mainly dependent on the active fuel length(L) and the core power (q)

.The riser height =f(L,q)

An increase in power rates is possible with increase in riser height, Yet the riser height cannot be indefinitely increased because of economical considerations.Thus the riser height has been limited to 10m

TABLE 7.1 :CHFR vs recirculation flow

G (kg/s.bundle)	pd = 42kw/lit		pd = 50kw/lit	
	CHFR result obtained	CPR result in ref1	CHFR result obtained	CPR result in ref1
4.000	0.739	1.0	0.621	0.85
5.000	0.891	1.12	0.748	0.95
6.000	1.027	1.24	0.863	1.05
7.000	1.148	1.35	0.964	1.15
8.000	1.255	1.45	1.054	1.20
9.000	1.349	—	1.133	1.25
10.00	—	—	1.201	1.35
11.0	—	—	1.261	—
12.0	—	—	1.311	—



G 7.1 CHFR VS MIN RECIRCULATION FLOW

Graphstar

TABLE 7.2 : minimum G vs active fuel length

active fuel length(l)	minimum flow rate	
	pd- 42 kw/lit	pd = 50kw/lit
(in m)	kg/s bundle	kg/s bundle
2.40	7.50	10.10
2.50	7.90	10.70
2.60	8.20	11.30
2.70	8.60	11.90
2.80	9.00	12.60
2.90	9.40	13.30
3.00	9.80	14.00
3.10	10.20	14.80
3.20	10.60	15.60

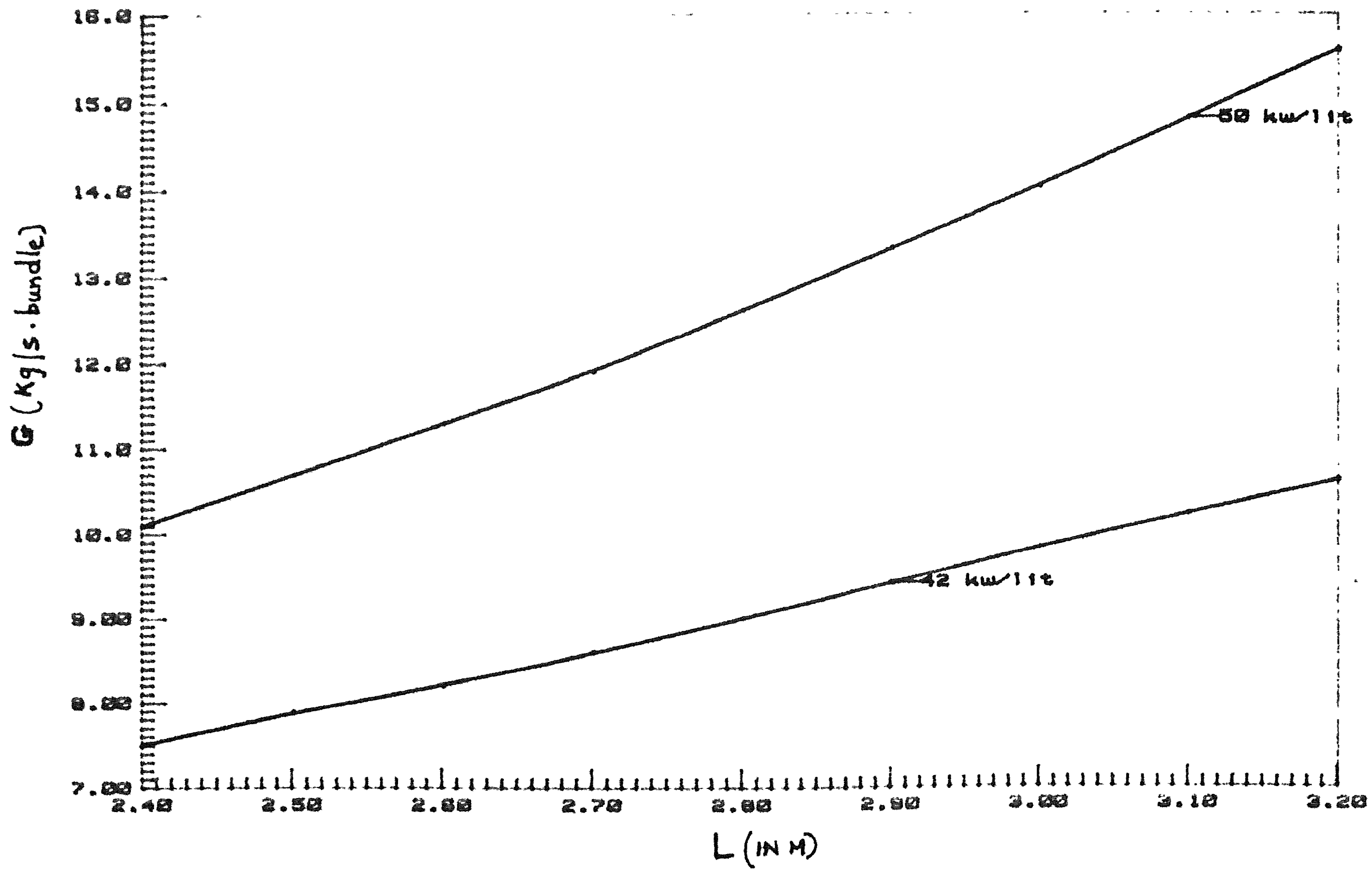


FIG 7.2 MIN G VS ACTIVE FUEL LENGTH

TABLE 7.3 :riser height vs active fuel length

active fuel length(in m)	RISER HEIGHT (in m)			
	pd= 50kw/lit		pd=42kw/lit	
	result obtained	from ref1	result obtained	from ref1
2.40	3.59	3.80	1.38	1.33
2.50	4.32	4.50	1.76	1.67
2.60	5.12	5.50	2.13	2.0
2.70	5.99	6.40	2.58	2.5
2.80	7.04	7.50	3.08	3.0
2.90	8.19	9.0	3.61	3.4
3.00	9.45	10.2	4.19	4.0
3.10	10.94	11.20	4.82	4.6
3.20	12.60	—	5.85	—

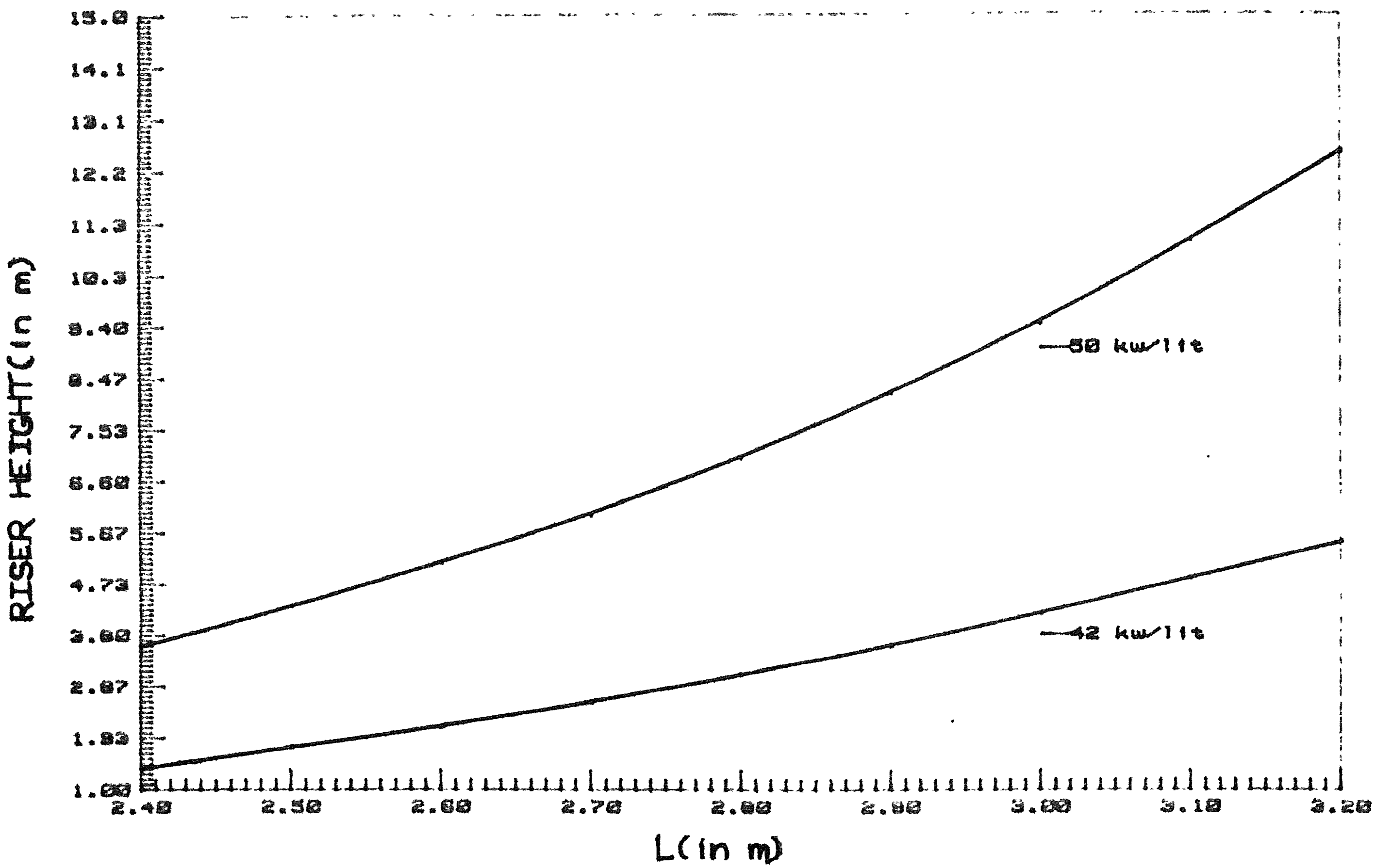


Fig 7.3 RISER HEIGHT VS ACTIVE FUEL LENGTH

TABLE 7.4: riser height at different power densities

power density (kw/lit)	RISER HEIGHT(in m)		
	l= 2.4m	l=2.7m	l= 3.2m
42	1.38	2.58	5.85
43	1.61	2.88	6.1
44	1.81	3.25	6.74
45	2.05	3.64	7.41
46	2.35	4.04	8.22
47	2.62	4.46	9.07
48	2.89	4.9	10.08
49	3.23	5.43	11.15
50	3.59	5.99	12.6

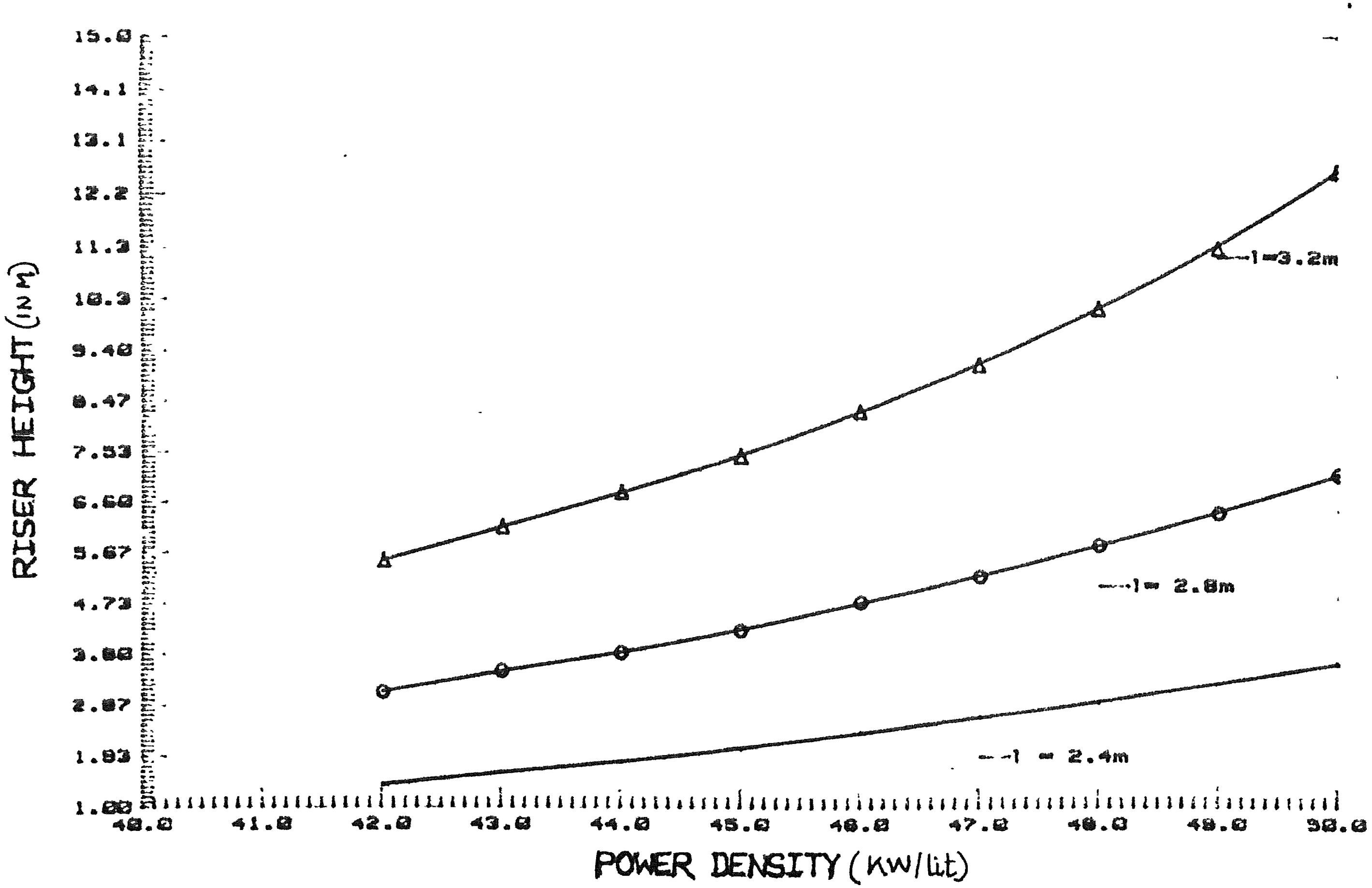


FIG 7.4 RISER HT VS POWER DENSITY

7.1.3 flow distribution in the core

The flow distribution in the core channel has been calculated according to the procedure outlined in Chapter 6.This has been done for two total core flows of 6 and 9.6 kg/s bundle.The flow distribution obtained has been shown in the tables 7.5 & 7.6.The riser height computed has also been shown in the tables.It clearly shows that the core flow will be the highest in the core channels with the highest heat generation (corresponding to the core channel with the highest neutron flux distribution.)

7.2 CONCLUSION

The thermal hydraulic requirement for CHFR was studied for the natural circulation boiling water reactor.The necessary riser height was calculated to establish the required flow in such reactors.It is concluded that natural circulation BWRs of higher power rates will be feasible even if major restrictions on the reactor pressure vessel diameter and riser height are set .Also the results are in general agreement with the published results of Akira Yasuo et al.(1) (refer to table 7.2 for comparison with published results)

The main conclusions are as follows

(1) With increase in core flow, the critical heat flux ratio increases.

(2) The core flow can be maintained using a certain riser height.

(3) The necessary riser height is a simple function of power density and active fuel length.

TABLE 7.5 :flow distribution pattern

for average flow of 6.0 kg/s.bundle

REGION	FLOW(in kg/s.bundle)
A	8.74
B	7.83
C	6.90
D	6.14
E	5.39
F	4.36
G	3.32

valu of riser height is = 2.5m

TABLE 7.6:flow distribution pattern

for average flow of 9.6 kg/s.bundle

REGION	FLOW
A	15.79
B	12.68
C	10.85
D	9.52
E	8.27
F	6.63
G	5.02

valu of riser height is 6.5m

CHAPTER 8

RECOMMENDATIONS FOR FUTURE WORK

(1) It is desirable to use the GEXL correlation for determining the Critical Power Ratio (CPR) as it will give more accurate and dependable results.(CPR is defined in chapter 4)

(2) The model taken for analysis in this study is one - dimensional.The flow distribution should be calculated using a the radial heat distribution (for eg. the Bessel function) while satisfying the Critical Power Ratio requirement.The riser height should be calculated accordingly as outlined in Chapter 6.

(3)The heat distribution in the axial direction has been taken to be strictly sinusoidal.The work can be extended to other heat distributions which are not strictly sinusoidal(as is the case actually) like the chopped cosine function,and a heat distribution in which the maximum value has been shifted closer to the bottom as in actual reactors.

(4) The pressure drops should be calculated more extensively by taking into account the spacers,support plate loss coefficient; also examining the case of riser height with separators.The accuracy of the riser height calculation is affected greatly by the accuracy of the pressure drop calculation.

(5)The study of change of parameters like pressure, no. of bundles should be done to get a more detailed idea of such reactors.

(6) The case of Natural Circulation BWRs with external recirculation can also be examined.

REACTOR SPECIFICATIONS

Operating pressure(MPa)	7.0
core inlet sub cooling(KJ/kg)	33.0
core diameter	5.8m
fuel bundle type	8x8
no of fuel bundles	872
active fuel length	2.4-3.2m
radial peaking factor	0.65-1.4
axial peaking factor	1.57.
fuel pin diameter	14.2mm
fuel channel dimension	0.138x0.138m

APPENDIX B

{ This program has been used to calculate the riser height.The minimum recirculation has been computed by the procedure crit.The Function nbh is used to compute the non- boiling height. The procedures bhd1 and bhd2 compute the average boiling densities in the core.The riser height has been finally calculated by equating the pressure drops and the driving pressure.}

```
program natur_circ(input,output);
const
pi=3.1415927;
hf=1258.18;
hg=2767.16;
hfg=1511.48;
hfeed=168;
vf=0.0014;
vi=0.0013;
s=3.5;
pf=714.28;
pg=35.71;
nob=872;
mul=2.48E-03;
var
  c1,c2,c3,c4:real;
  d:real;
  deltah:real;
  dpr:string;
  g,pd,l:real;
  vfg,vg,hi,m,mg,qs,qt:real;
  f1,f2,ho,hb:real;
  i:integer;
  gunit,A1,a2,alphae,vl:real;
  reyn,prf,frf,R_,rac,accprd:real;
  hyd:real;
  sppad,tpprd:real;
  pe,si,pb,po,xe:real;
  frch,frdc:string;
  remprd,dco,pave,hch:real;
```

```
function nbh(pi,l,qs,qt:real):real;
var
x,y,u,v:real;
begin
x:=qs/qt;
y:=1-2*x;
u:=sqrt(1+y*y);
v:=u/y;
nbh:=arctan(v)*l/pi
end;
{______________________________________________________________}
function bhd1(pi,pf,pg,c1,c2,c3,c4,ho,hb,l:real):real;
var x,y,z:real;
begin
  x:=sin((pi*ho)/(2.0*l))/cos((pi*ho)/(2.0*l));
  y:=ln((c4-c3)*x +sqrt(c4*c4-c3*c3))
  -ln((c4-c3)*x-sqrt(c4*c4-c3*c3));
  z:=y*((c1*c4-c2*c3)*l)/(c4*sqrt(c4*c4-c3*c3)*hb*pi);
  bhd1:=pf-(pf-pg)*(c2/c4-z)
end;
{______________________________________________________________}
procedure bhd2(pb,pi,pf,pg,c1,c2,c3,c4,ho,hb,l:real);
var x,y,z:real;
begin
x:=sin(pi*ho/(2.0*l))/cos(pi*ho/(2.0*l));
y:=1.0-2.0/pi*arctan((c3-c4)*x/sqrt(c3*c3-c4*c4));
z:=(c1*c4-c2*c3)*l/(c4*sqrt(c3*c3-c4*c4)*hb);
pb:=pf-(pf-pg)*(c2/c4+y*z);
end;
{______________________________________________________________}
procedure crit(var  pd,l,g:real);
const
pb=70;
a1=0.0088;
d=0.010;
hs=33;
hfg=1511.48;
var
  hb:real;
```

```
        g2,qcr,cpr:real;
        z:real;
        i:integer;
  begin
   cpr:=0.0;
   g:=1.0;
   while (cpr<=1.30) do
     begin
       g2:=g/a1;
       hb:=-1.159+0.149*pb*exp(-0.019*pb)+9*pb/(10+pb*pb);
       z:=1.0+4*1*15.048*exp(7*ln(10))*exp(-0.6*ln(g2))*hb/(g2*d*hfg*1000);
       qcr:=150.48*exp(-0.6*ln(g2))*hb*(1+hs/hfg)/z;
       cpr:=qcr/(pd/42000*0.802);
       g:=g+0.1
     end
  end;
{_______________________________________________________________}
 begin{    main program}
pd:=42000;
while (pd<=50000) do
begin
   writeln('for power density',pd);
   l:=2.4;
   while (l<=3.2) do
     begin
     crit(pd,l,g);
dco:=5.8;
vg:=1/pg;
 m:=g*nob;
 deltah:=33.0;
 hi:=hf-deltah;
 d:=(hi-hfeed)/(hf-hfeed);
 mg:=(pd*pi*dco*dco*l/4.0-m*deltah)/hfg;
 xe:=mg/m;
 po:=2/(vi+vf);
 qt:=hf+(xe*hfg)-hi;
 qs:=deltah;
 c1:=qt/(2*hfg)-(hf-hi)/hfg;
 c2:=-qt/(2*hfg);
```

```
 si:=pg/pf*s;
hyd:=0.01024;
 A1:=0.01907;
 a2:=0.008827;
 gunit:=g/a2;
 vl:=0.95*g/6.0;
 reyn:=hyd*pf*vl/mul;
 alphae:=xe/(si+(1.0-si)*xe);
 pe:=alphae*pg+(1.0-alphae)*pf;
 frf:=0.184/exp(0.2*ln(reyn));
R_:=1.0/3.0*(1.0+1.0/(1.0-alphae)+sqr(1.0/(1.0-alphae)));
rac:=vf*(sqr(1.0-xe)/(1.0-alphae)+sqr(xe)/alphae*vg/vf-1.0);
accprd:=rac*sqr(gunit);
sppad:=-0.7*(1.0/A1*A1-1.0/(a2*a2))*g/pf*g;
tpprd:=(1.0/(A1*a2)-1.0/(A1*A1))*g*g*(sqr(1.0-xe)/(pf*(1.0-alphae))+xe*xe/
c3:=si+(1.0-si)*c1;
 c4:=(1-si)*c2;
ho:= nbh(pi,l,qs,qt);
hb:=l-ho;
prf:=frf*pf*sqr(vl)*(ho+R_*hb)/(2.0*hyd);
if sqr(c4)>sqr(c3)
then begin
     pb:=bhd1(pi,pf,pg,c1,c2,c3,c4,ho,hb,l);
     end
     else begin
             bhd2(pb,pi,pf,pg,c1,c2,c3,c4,ho,hb,l);
          end;
f1:=frf*sqr(m*4.0/(pi*pe*dco*dco))*pe/(2.0*dco);
f2:=frf*sqr(m*4.0/(pf*pi*10.456))*pf/(2.0*1.056);
remprd:=accprd+sppad+tpprd+prf;
pave:=1/l*(po*ho+pb*hb);
hch:=(9.81*pf*l-9.81*pave*l-f2*l-remprd)/(f1+f2-9.81*pf+pe*9.81);
 writeln(' ',l:10:2,'  ',g:10:2,' ',hch:10:2);
 l:=l+0.1
 end;
 pd:=pd+1000
 end;
 end.
```

APPENDIX C

```
{This program divides the core into different regions
 and counts the no. of grids in different regions}
program grid_cnt(output);
 const
 dtx=0.138;
 type
 string=array[1..219] of real;
 var
 cx,cy,cd:string;
 i,j,k:integer;
 cnt0,cnt1,cnt2,cnt3,cnt4,cnt5,cnt6:integer;
{-----------------------------------------------------------}
 begin
   cx[1]:=1.863;
   cy[1]:=0.069;
 for i:=2 to 196 do
 begin
   j:=(i-1) mod 14;
   cx[i]:=cx[1]-j*dtx;
   k:=i div 15;
   cy[i]:=cy[1]+k*dtx
end;
   for i:=197 to 207 do
 begin
  cx[197]:=cx[1]-3*dtx;
  cy[i]:=cy[183]+dtx;
  j:=i-197;
  cx[i]:=cx[197]-j*dtx
end;
for i:=208 to 218 do
    begin
       j:=197+i-208;
       cx[i]:=cx[j];
       cy[i]:=cy[j];
    end;
    cnt0:=0;
    cnt1:=0;
```

```
cnt2:=0;
cnt3:=0;
cnt4:=0;
cnt5:=0;
cnt6:=0;
for i:=1 to 218 do
begin
cd[i]:=sqrt(cx[i]*cx[i]+cy[i]*cy[i]);
if (cd[i] <0.6) then
cnt0:=cnt0+1;
if ((0.6<=cd[i])and (cd[i] < 1.00)) then
cnt1:=cnt1+1;
if(( 1.00<=cd[i])and (cd[i] < 1.30)) then
cnt2:=cnt2+1;
if(( 1.30<=cd[i])and(cd[i] < 1.60)) then
cnt3:=cnt3+1;
if(( 1.60<=cd[i])and(cd[i] < 1.90)) then
cnt4:=cnt4+1;
if(( 1.90<=cd[i])and(cd[i] < 2.10)) then
cnt5:=cnt5+1;
if(( 2.10<=cd[i])and(cd[i] < 2.40)) then
cnt6:=cnt6+1;
end;
writeln('the valu of cnt0 is',cnt0);
writeln('the valu of cnt1 is ',cnt1);
writeln('the valu of cnt2 is ',cnt2);
writeln('the valu of cnt3 is ',cnt3);
writeln('the valu of cnt4 is ',cnt4);
writeln('the valu of cnt5 is ',cnt5);
writeln('the valu of cnt6 is ',cnt6);
end.
```

APPENDIX D

```
{This program is for calculation of fluid flow distribution

pattern }

program natur_circ(input,output);
type
   list1=array[1..7] of real;
var
  k:integer;
  pof,nob,xe,m1,hch,g1:list1;
  mav,xav,mcum,xcum:real;
procedure rsrht(var xe,pof,nob,m1,hch:list1);
const
pi=3.1415927;
hf=1258.18;
hg=2767.16;
hfg=1511.48;
hfeed=168;
l =2.7;
vf=0.0014;
vi=0.0013;
s=3.1;
pf=714.28;
pg=35.71;
qv=42000;
mul=2.48E-03;
var
  c1,c2,c3,c4:real;
  d:real;
  deltah:real;
  dpr:real;
  pd,g:real;
vfg,vg,hi,m,mg,qs,qt:real;
  f1,f2,ho,hb:real;
  i:integer;
  gunit,A1,a2,alphae1,alphae,vl:real;
  reyn,prf,frf,R_,rac,accprd:real;
  hyd:real;
  sppad,tpprd:real;
```

```
      vl1,frfl,reynl:real;
      pe,pel,si,pb,po,xel:real;
      frch,frdc:real;
      resprd:real;
      totprd:real;
     dco:real;
     pave:real;
{________________________________________________________________}
   function nbh(pi,l,qs,qt:real):real;
   var
   x,y,u,v:real;
   begin
   x:=qs/qt;
   y:=1-2*x;
   u:=sqrt(1+y*y);
   v:=u/y;
   nbh:=arctan(v)*l/pi
  end;
{________________________________________________________________}
  function bhd1(pi,pf,pg,c1,c2,c3,c4,ho,hb,l:real):real;
  var x,y,z:real;
  begin
  x:=sin((pi*ho)/(2.0*l))/cos((pi*ho)/(2.0*l));
  y:=ln((c4-c3)*x +sqrt(c4*c4-c3*c3))
     -ln((c4-c3)*x-sqrt(c4*c4-c3*c3));
 z:=y*((c1*c4-c2*c3)*l)/(c4*sqrt(c4*c4-c3*c3)*hb*pi);
 bhd1:=pf-(pf-pg)*(c2/c4-z)
 end;
{_______________________________________________________________}
procedure bhd2(pb,pi,pf,pg,c1,c2,c3,c4,ho,hb,l:real);
var x,y,z:real;
begin
x:=sin(pi*ho/(2.0*l))/cos(pi*ho/(2.0*l));
y:=1.0-2.0/pi*arctan((c3-c4)*x/sqrt(c3*c3-c4*c4));
z:=(c1*c4-c2*c3)*l/(c4*sqrt(c3*c3-c4*c4)*hb);
pb:=pf-(pf-pg)*(c2/c4+y*z);
end;
{______________________________________________________________}
begin
```

```
dxo:=5.8;
vg:=1/pg;
 m:=6.0*872.0;
 deltah:=33.0;
 hi:=hf-deltah;
 d:=(hi-hfeed)/(hf-hfeed);
{ writeln('the value of d is',d);}
 xe1:=0.357;
 {writeln('the value of xe[k] is',xe[k]);}
 m1[k]:=(pof[k]*2.1781*qv*nob[k]*0.138*0.138*1)/(xe[k]*hfg+deltah);
 {mg/xe[k];}
 po:=2/(vi+vf);
 qt:=hf+(xe[k]*hfg)-hi;
 qs:=deltah;
 c1:=qt/(2*hfg)-(hf-hi)/hfg;
 c2:=-qt/(2*hfg);
 si:=pg/pf*s;
hyd:=0.01024;
 A1:=0.01907;
 a2:=0.008827;
 g:=m1[k]/nob[k];
 {writeln('valu of g is',g);}
 gunit:=g/a2;
 v1:=0.95;
 v11:=0.95*g/6.0;
 reyn:=hyd*pf*v1/mul;
 reyn1:=hyd*pf*v11/mul;
 alphae1:=xe1/(si+(1.0-si)*xe1);
 alphae:=xe[k]/(si+(1.0-si)*xe[k]);
 pe:=alphae*pg+(1.0-alphae)*pf;
 pe1:=alphae1*pg+(1.0-alphae1)*pf;
 frf:=0.184/exp(0.2*ln(reyn));
 frf1:=0.184/exp(0.2*ln(reyn1));
R_:=1.0/3.0*(1.0+1.0/(1.0-alphae)+sqr(1.0/(1.0-alphae)));
rac:=vf*(sqr(1.0-xe[k])/(1.0-alphae)+sqr(xe[k])/alphae*vg/vf-1.0);
accprd:=rac*sqr(gunit);
sppad:=-0.7*(1.0/A1*A1-1.0/(a2*a2))*g/pf*g;
tpprd:=(1.0/(A1*a2)-1.0/(A1*A1))*g*g*(sqr(1.0-xe[k])
/(pf*(1.0-alphae))+xe[k]*xe[k]/(pg*alphae));
```

```
c3:=si+(1.0-si)*c1;
 c4:=(1-si)*c2;
ho:= nbh(pi,l,qs,qt);
hb:=l-ho;
{writeln('the value of non_boiling height is',ho);}
{writeln('the value of boiling height is',hb);}
prf:=frf*pf*sqr(vl)*(ho+R_*hb)/(2.0*hyd);
if sqr(c4)>sqr(c3)
  then begin
         pb:=bhd1(pi,pf,pg,c1,c2,c3,c4,ho,hb,l);
     end
else begin
      bhd2(pb,pi,pf,pg,c1,c2,c3,c4,ho,hb,l);
     end;
f1:=frf1*sqr(m*4.0/(pi*pe1*dco*dco))*pe1/(2.0*dco);
f2:=frf1*sqr(m*4.0/(pf*pi*10.456))*pf/(2.0*1.056);
remprd:=accprd+sppad+tpprd+prf;
pave:=1/l*(po*ho+pb*hb);
hch[k]:=(9.81*pf*l-9.81*pave*l-f2*l-remprd)/(f1+f2-9.81*pf+pe*9.81);
end;
 begin{main program}
 xe[1]:=0.33;
for k:=2 to 7 do
     xe[k]:=0.30;
nob[1]:=60;
nob[2]:=104;
nob[3]:=112;
nob[4]:=176;
nob[5]:=224;
nob[6]:=100;
nob[7]:=96;
pof[1]:=0.988;
pof[2]:=0.92;
pof[3]:=0.84;
pof[4]:=0.7652;
pof[5]:= 0.685;
pof[6]:=0.567;
pof[7]:=0.44;
for k:=1 to 1 do
```

```
   rsrht(xe,pof,nob,m1,hch);
for k:=2 to 7 do
[k]:=0.5;
for k:=2 to 7 do
begin
    while(hch[k]<=hch[1]) do
   begin
      rsrht(xe,pof,nob,m1,hch);
      xe[k]:=xe[k]+0.001
          end
end;
mcum:=0.0;
xcum:=0.0;
k:=1;
while(k<=7) do
begin
mcum:=mcum+m1[k];
xcum:=xcum+m1[k]*xe[k];
g1[k]:=m1[k]/nob[k];
writeln('   ',g1[k]:10:2,'  ',xe[k]:10:2,'  ',hch[k]:10:2);
k:=k+1
end;
mav:=mcum/872;
xav:=xcum/(mav*872);
writeln('valu of xav is',xav:15:2);
writeln('valu of mav is',mav:15:2);
end.{main program}
```

APPENDIX E

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